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MODELING, EXERGY ANALYSIS AND OPTIMIZATION OF CEMENT PLANT INDUSTRY

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Abstract: This study investigates the recovery of wasted heat in the cement plant industries (Neka Cement Factory) in order to reduce the use of fossil fuels and greenhouse gas emissions. Cement is the most widely used man-made material. The global cement industry produces about 3.3 billion tons of cement annually. A lot of energy is needed to produce cement. About 200 kg of coal is used to produce each ton of cement. The cement industry also produces about five percent of the world's greenhouse gases. The method studied in this research is based on heat recovery from boilers installed at the outlet of a clinker cooler and a preheater in a cement factory. Due to the low temperature of the gases available, three different fluids, i.e. water, R134a and R245fa were considered as the operating fluids. Also, energy and exergy analyses are performed in a Rankin cycle and the selection of optimal parameters is considered by using genetic algorithm. The results of this study showed that water with optimized parameters leads to an increase in the production capacity from 5 to 9 MW. However, fluid R134a with optimized parameters leads to a 4% increase in exergy losses and it also increases the production capacity from 5 to 9 MW.

Keywords: exergy, organic rankine cycle, thermodynamic analysis, cement plant

1. INTRODUCTION

The construction industry became aware of the concept regarding sustainable development from the ongoing threat of growing population and over-urbanization. The rapid economic growth galvanized the increasing demand for building construction. In general, buildings consume more than 30% of total global energy [1] and an immense amount of raw materials, such as 70% of global timber [2]. Supplying energy to the construction sector relies mainly on fossil fuels. The continuous consumption of fossil fuels to supply energy, abruptly increased carbon emissions from 280 ppm to 391 ppm in 2011, eventually rising over 400 ppm in 2014 [3]. Comparing the industry, transpor and building sectors in several countries between 1990 and 2050, highlights the rising energy consumption and over exploitation of natural resources, specifically in the building sector [4]. Worldwide awareness towards environmental impacts of resource depletion, energy shortage, climate change, and greenhouse gas emissions sparked concern about energy consumption trends placing tremendous pressure on the construction industry. As a result, the term of sustainable construction has become more familiar in the global construction market. Sustainable construction aims to achieve safe and secure buildings with a minimum impact on society, environment, and economy. The movement towards energy optimization, which began in the world in the early 1970s, has always carried the three issues of energy, economy and environment as the main bases. Industrialized countries have made significant economic gains in return for this move, while raising their environmental standards. Today, these countries consider energy optimization and management as a new source of energy. Among these, one of the most important energy optimization strategies implemented in all these countries with the aim of increasing energy efficiency and optimal use of fuel resources with an overall efficiency of 75 to 95%, is the use of simultaneous generation of electricity and heat [5]. Simultaneous generation of electricity and heat technologies generates electricity or mechanical power and it significantly recovers excess heat for a variety of uses. In simultaneous technologies, excess heat generated by electricity generation or mechanical power is recycled to reuse energy for a variety of uses. The use of these technologies is due to the considerable losses when converting thermal energy into mechanical or electrical energy. Cement is one of the products of non-metallic mineral industry. Due to its wide range of consumption, it is considered as one of the basic goods and the main source of development. This product is so intertwined with human life that the rich and poor nations each benefit from its effects. Cement production and consumption per capita is one of the indicators of growth and development in today's economy. The increasing consumption of cement and the need to reduce and finally completely cut the dependence on imports has caused a lot of attention to this industry. Currently, the cement industry is one of the industrial bases of any country. Due to the fact that Iran is one of the earthquake-prone regions of the world and the highest number and strongest earthquakes have occurred in this country, the reconstruction of earthquake-stricken areas and compliance with the principles and standards of manufacturing engineering increases the need for cement. One of the technologies that is able to recover heat dissipation in various industrial processes is called the organic Rankin cycle (ORC). The simple organic Rankine cycle consists of four parts: condenser, pump, evaporator and turbine. Utilization of different types of low temperature sources is the most important feature of organic Rankine cycles, which has been achieved by using a fluid other than water. Organic fluids, refrigerants and mixed fluids usage is a feature that distinguishes organic Rankine cycles from the Rankine vapor cycle and has made it superior in low and medium temperature applications. Another advantage of the organic Rankine cycle is its small size and simplicity. Another important issue is the environmental conditions of this cycle and its effects on climate. Because organic Rankine cycles are closed, they do not produce any pollutants such as solids, liquids or gases, CO, CO2 and NOx which is of particular importance in today's world where environmental pollution is a serious issue. Al-Sulaiman [6] showed that using the triple fuel cell system and organic increases the efficiency of the triple system by about 22% compared to the cogeneration system. In this case, the highest efficiency of the triple unit was 74% and 71% for the dual unit of heat production, 57% for the dual unit of cold production and 46% for the single unit. Most energy-intensive industrial processes, such as heat engines and mechanical equipment, have high amounts of heat loss. Cement is one of the industries with high energy consumption so that calcination, drying processes as well as kiln, require high amounts of heat. Garg *et al.* investigated the potential for heat recovery from the low-temperature combustion engine using organic Rankine cycles to achieve high efficiencies [7]. By using the heat of the hot exhaust gas from the engine and combining it with organic Rankine cycles, the fuel conversion efficiency is improved by an average of 7%. This is while the NOx output decreases by an average of 18%. In order to recover heat from the exhaust gases of the preheater and the great cooler at the cement plant, Wang *et al.* proposed a single-pressure cycle, a two-pressure steam cycle, an organic Rankin cycle, and a Kalina cycle to generate dual-purpose electricity and heat [8]. Under the same conditions, they studied the parameters obtained from the optimization by the genetic algorithm in order to achieve the maximum exergy efficiency. Comparison with other systems shows that the best performance in the cement plant can be achieved with the Kalina cycle. Campana *et al.* conducted the first comprehensive study of Rankin organic cycle units for factories in operation or under construction, such as the cement, steel, glass, and oil and gas industries in 27 EU countries [9]. This study showed that more than 20,000 gigawatt hours of thermal energy per year can be recovered and 7.6 million tons of it can be stored by using Rankin organic cycle technology. They also showed that the best available method for heat recovery in the cement industry is the use of the Rankin organic cycle and steam cycle technology [10]. Nazari *et al.* [11] proposed the sub-steam Rankin cycle combined with the organic Rankin cycle to recover wasted heat from a gas turbine. They conducted a parametric study to investigate the effect of important parameters such as: organic turbine inlet pressure, organic preheater temperature and organic condensation temperature. Many industrial plants use recycled heat in the production process to heat water or circulating fluid in the environment. Due to the high temperature in this section (the cooler and the preheater outlet), it is better to use the heat available to generate electrical energy. Different cycle parameters such as heat source types, operating conditions and temperature level can greatly affect the cycle performance. It was demonstrated that increasing the heat source and the compression temperature has positive and negative effects on the performance of organic Rankine cycles, respectively. However, other parameters showed different effects on the performance of the cycle and these usually determine the optimal operating parameters for each cycle. Integrated organic Rankine cycles with the cement production line can have good economic performance and reduce gas emissions. The economic performance of organic Rankine cycles applied in the cement industry is improved by increasing the scale of application. The purpose of this study is to design an organic Rankine cycle with simultaneous generation of electricity and heat in a cement factory (the case study: the Neka cement factory). In this technology, hot air from the preheater and also from the clinker cooler is directed to the recycling boiler and it converts water to steam, and then this steam is directed to the steam turbine, without affecting the quantity and quality of the clinker produced.

2. RESEARCH METHODOLOGY

The Neka cement plant is located at 3 km southeast of the city of Neka, northern Iran, with two gray cement production lines and a nominal capacity of 4,000 and 3,000 tons of clinker per day. A schematic diagram of the cement plant case study which is located in the city of Neka with the Rankine cycle is shown in Fig. 1.

It took two years to finish the project (started in 2008) to increase the capacity of Line 1 to reach 4,000 tone clinker per day. Raw materials for portland cement production in the Neka cement factory consist of 70-75% limestone, 20-25% clay supplied from the factory's mine, as well as 4-6% silica and 1.5-2% iron ore from outside the factory. The composition of the raw materials and their mixing ratio is such that compounds such as calcium oxide, silica, alumina and iron oxide are in a certain range and disturbing oxides are below the allowable limit. At first, limestone and soil are extracted from the mine and they enter the two crushers of the factory by truck and are crushed to less than 10 cm. Due to the geographical location of the region and rainfall levels characteristic for this area, clay and silica, which have high amounts of moisture, are dried in a rotary dryer, which is very similar to a cement kiln, to prevent material clogging in different parts. In Neka cement, this process takes place in three roller mills. Before storing the powdered material in silos, the raw material is automatically sampled from the powder obtained in the laboratory. After an X-ray analysis or an analytical analysis, as well as some physical tests and some necessary adjustments, the materials enter the silo. What is obtained from the silos is called kiln feed, and this feed is such that after cooking in the cooking system, it produces clinker with the required composition. In four silos, the raw materials are stored and homogenized. After preparing and arranging the raw materials and making sure that the composition is suitable, these materials are ready for cooking. The furnace feed enters the cyclone preheater and calciner. The task of the preheater and calciner is to capture the remaining surface moisture in the raw materials, evaporate the crystallized water and preliminary decomposition of the silicates. An important part of the baking process takes place in the rotary oven. The Neka cement factory has two furnaces. The length and diameter of one furnace is 70 and 4.60 meters respectively and the length of the second furnace is 52 meters and its diameter is 4.4 meters. The capacity of the first furnace has increased from 2,000 to 4,000 tons and the design capacity of the second furnace is 3,300 tons of clinker per day. At the bottom of the furnaces, there is a burner that uses natural gas fuel or fuel oil to create a thermal environment with a temperature of 1,500 degrees Celsius. The furnace feed is first fully calcined along the furnace pathway, the silicates are decomposed and then the oxides begin to combine. At the end and after the completion of the reactions in the cooking zone, the clinker leaves the oven in the form of dark grains. The output clinker from the furnace has a temperature of about 1,300-1,400 degrees. Recovering this amount of heat, as well as the difficulty of moving the hot clinker, necessitates cooling. Another basic property of clinker cooling is to stabilize the shape of clinker crystals and to increase its quality. Neka cement coolers have a capacity of 4,400 and 3,600 tons of clinker per day and cool the clinker temperature to 65 degrees above ambient temperature [12]. The coolant outlet clinker enters the four clinker silos. Four ball mills are used to powder the clinker from the curing system. In this part of the production line, along with the input clinker, about four percent of gypsum is added to the cement mill, and the powder obtained from the mill is known as cement. Therefore, the maximum superheated steam temperature can be equal to this value [13]. After being baked at a temperature of 1,200 °C in a rotary kiln, clinker needs to be cooled. The second source of heat is obtained by gases from the clinker cooler (300 °C) and is recovered by the heat exchanger (an AQC boiler). Heat exchangers usually operate with diathermic oil that the temperature is maintained at a stable value. Then the heat is transferred from diathermic oil to organic fluid and, in the ORC unit, electricity is generated. In the current study, researchers used a MATLAB/Simulink package v9.10.0 to simulate the Neka cement factory with the organic Rankine cycle. Air is considered as a mixture of gases (Table 1) and its thermo physical characteristics are defined as a function of temperature.

Figure 2 shows a schematic of the cement plant case study which is located in the city of Neka with Rankine cycle (red area).

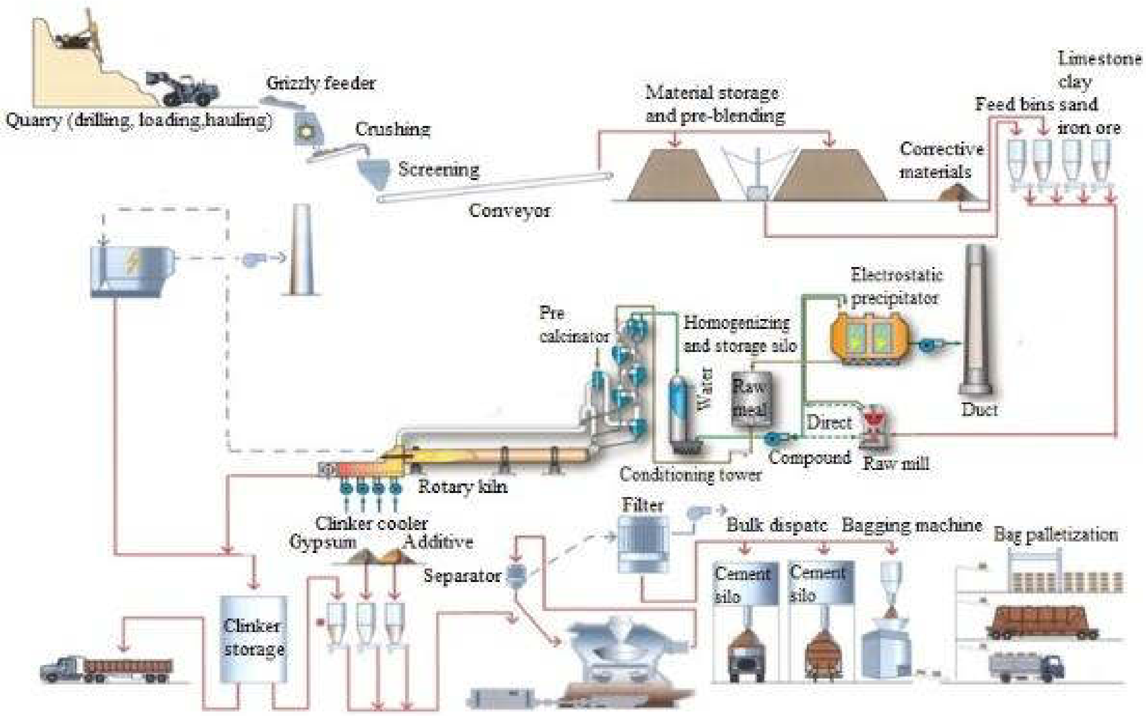

Fig. 1. Schematic view of cement production process in Neka cement factory

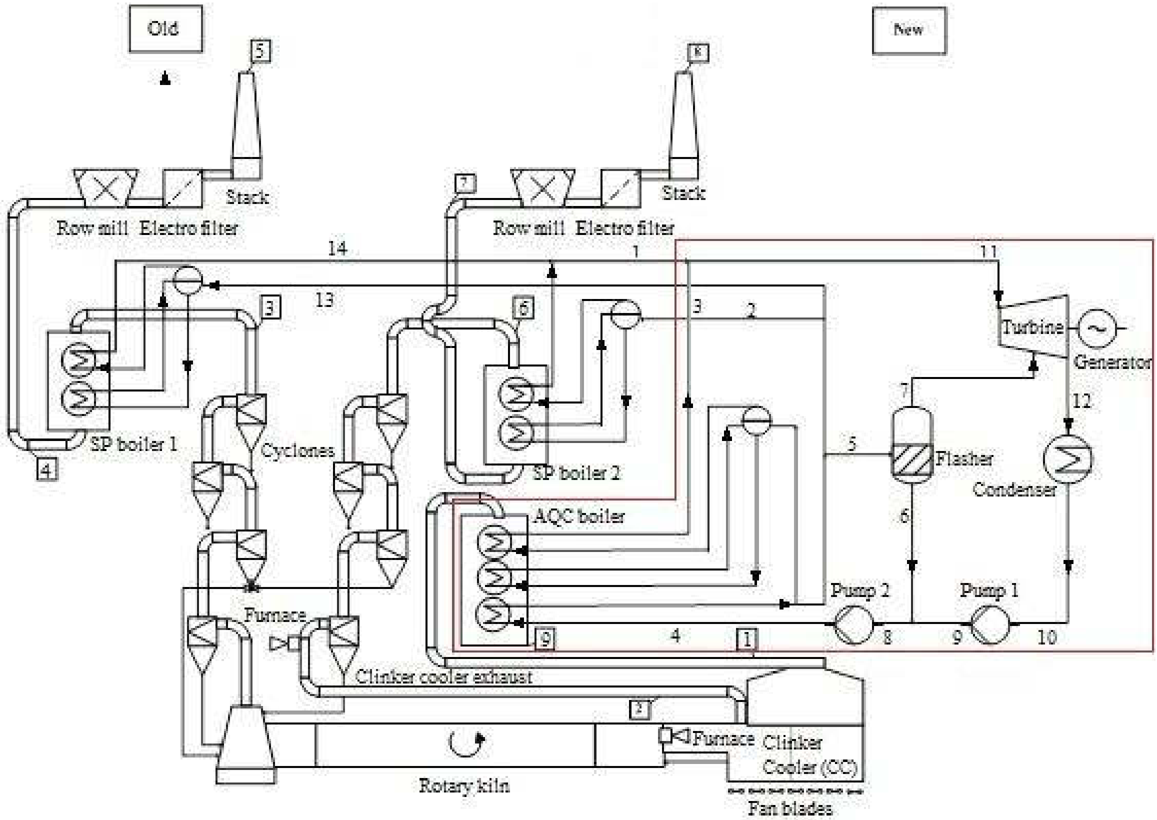

Fig. 2. Schematic diagram of organic Rankine cycle and Neka cement industry for waste heat recovery

The thermodynamic cycle includes an expansion process (11-12), a condensation process (12-10), a pumping process (pump 1) (10-9), a pumping process (pump 2) (8-4) and an evaporation process (4-3). The following assumptions are made to simplify the analysis:

1. The steady flow and heat transfer state within the ORC.
2. The saturated liquid state at the condenser outlet.
3. The saturated vapor state at the evaporator outlet.
4. No heat loss from the ORC component to the environment.
5. No pressure drops with fluid flowing in pipelines.

Tab. 1. Air Mixture percent

Air Components	Molar fraction (%)
N_2	75.67
O_2	20.35
H2O	3.03
CO_2	0.0345
CO	0.0007
SO_2	0.0002
H_2	0.00005
Others	0.91455

Three different fluids, i.e. water, R134a and R245fa were selected. R134a and R245fa are HFC refrigerants and therefore have no effect on the ozone layer. These refrigerants are non-flammable and non-explosive and their toxicity is standard. To fulfill that, a steel preheater with an inlet air flow from clinker cooler fan blades is applied. To reach the desired temperature, the air flow is heated by a torch which is installed under the preheater. Line 1 of the plant is studied in this paper as a case study. The temperature profile and the properties of Line 1 are provided in Table 2.

Equations and its details for different parts of the ORC and Heat Recovery Steam Generator (HRSG) units are as follow:

Compressor exergy efficiency, turbine efficiency and thermal retention factors were 80%, 75%, and 90%, respectively [14].

The mass balance equation:

$$\sum \dot{m}_i = \sum \dot{m}_o. \tag{1}$$

The production or consumption of power and disposed or absorbed heat by each of the cycle components are calculated using the first and second laws of thermodynamic.

Tab. 2. Air Mixture percent

Point	Parameter	Temperature (°C)	Mass flow rate (kg/s)
1	Clinker cooler exhaust	290	56.33
2	New preheater entrance	899	31
3	Old preheater exhaust	311	42
4	SP boiler 1 exhaust	215	42
5	stack exhaust 1	93	42
6	New preheater exhaust	317	62
7	SP boiler 2 exhaust	215	62
8	stack exhaust 2	99	62
9	AQC boiler exhaust	99	56.33

The energy balance equation is used as follow:

$$\sum_i \dot{E}_i + \dot{Q} = \sum_o \dot{E}_o + \dot{W}, \tag{2}$$

Energy balances for the turbine cycle are as follows:
Evaporator:

$$\dot{Q}_{evap} = \dot{m}_i(h_o - h_i), \tag{3}$$

Turbine:

$$\eta_T = \frac{\dot{W}_{T,a}}{\dot{W}_{T,s}} = \frac{h_i - h_{o,a}}{h_i - h_{o,s}}, \tag{4}$$

$$\dot{W}_{T,a} = \sum \dot{m}_i h_i - \sum \dot{m}_o h_o, \tag{5}$$

Condenser:

$$\dot{Q}_{cond} = \sum \dot{m}_i h_i - \sum \dot{m}_o h_o, \tag{6}$$

Pressure drop in the evaporator were assumed as follows.

$$\frac{p_o}{p_i} = (1 - \Delta p), \tag{7}$$

Pump:

$$\eta_p = \frac{\dot{W}_{p,s}}{\dot{W}_{p,a}} = \frac{v_i(p_o - p_i)}{h_o - h_i}, \tag{8}$$

HRSG design in the project is based on the pinch and approach point which by considering these parameters as the input and the steam flow rate are calculated. Also, in the HRSG design, the steam and water temperature graph is determined and the inlet and outlet temperature of the heat exchanger are determined. Finally, given the prevailing limits such as the temperature of the exhausted gases and the lack of steam generation in the economizer etc., the design will be completed [15,16]. Both pinch points and approach points are considered in modeling.

$$T_{ap} = T_{sat} - T_{w,o}, \tag{9}$$

$$T_{pp} = T_{g,o,eva} - T_{sat}, \tag{10}$$

Mass and energy balance equations for the economizer, evaporator and superheater are given below:

Economizer:

$$\dot{m}_g Cp_g (T_{g,o} - T_{g,i}) = \dot{m}_f (h_{w,o} - h_{w,i}). \quad (11)$$

Evaporator:

$$\dot{m}_g Cp_g (T_{g,o} - T_{g,i}) = \dot{m}_f [(h_v - h_{w,o}) + BD(h_i - h_{w,o})]. \quad (12)$$

Super heater:

$$\dot{m}_g Cp_g (T_{g,o} - T_{g,i}) = \dot{m}_f (h_{s,o} - h_{s,i}). \quad (13)$$

In this paper, exergy at each point is a combination of physical and chemical exergy which is calculated according to the following equation [17-19]:

$$E_x = E_{x_{PH}} + E_{x_{CH}}, \quad (14)$$

Chemical exergy is considered in calculations with respect to the components of exhausted gases from the clinker cooler and the combustion products and this also covers the clinker production processes in the cement plant which are determined based on the data obtained from the plant studied. Also, the chemical exergy of each component is determined according to Table 3.

Tab. 3. Chemical exergy and molar mass of the main composition of the kiln feed

Chemical exergy (Kj/Kmol)	Molar mass	Composition
95700	172.28	$2Ca.SiO_2$
219800	251.46	$3Ca.SiO_2$
500600	270.3	$3Ca.\ Al_2O_3$
66700	486.1	$4Ca.Al_2O_3.Fe_2O_3$
66800	40.3	MgO
8200	136.166	$CaSo_4$
95700	172.28	$2Ca.\ SiO_2$
219800	251.46	$3Ca.\ SiO_2$

Exergy loss rate for each component is calculated according to the following equation [20]:

$$\dot{E}_{x_f} = \dot{E}_{x_e} + \dot{E}_{x_D} + \dot{E}_{x_L}. \quad (15)$$

Also, by defining the following parameter the rate of exergy loss to the total exergy loss can be achieved:

$$y_D = \frac{\dot{E}_{x_D}}{\dot{E}_{x_{D,total}}}, \quad (16)$$

Exergy efficiency of the cycle is calculated as follows:

$$\eta_{ex} = 1 - \frac{\dot{E}_{x_D} + \dot{E}_{x_L}}{\dot{E}_{x_{int,plant}}}, \quad (17)$$

$\dot{E}_{x_{int,plant}}$ is the resulted exergy from the outlet of clinker coolers and inlet preheater to the designed plant. It should be noted that the total exergy loss for boilers is defined based on the heat transfer in each boiler.

$$\xi = \frac{\dot{E}_{x_D}}{\dot{Q}_k}, \quad (18)$$

The genetic algorithm is the search method which is used for finding the exact or approximate solutions of the optimization problems. This method was first used by John Holland in 1960, and is now employed in many fields including engineering, chemistry, mathematics, physics, computational sciences, phylogenetic, etc. This algorithm is a special class of evolutionary algorithms, which have been inspired by evolutionary biology concepts. The computational procedure in this algorithm includes the following steps [21,22]:

1. Generating an initial population.
2. 2Evaluating the fitness of each individual in the population.
3. 3Repeating the optimization process until a termination cause is achieved.

The economic analysis of each component is determined according to the following references [14,29]. A steadied electricity price over the 20 years is calculated as follows:

$$\text{Cost} = \frac{\frac{i(1+i)^N}{(1+i)^N - 1} Z_{plant}}{E} + OM, \quad (19)$$

where

$$E = \sum_{t=0}^{6072} \dot{E}_{out}(t) \Delta t. \quad (20)$$

3. FINDINGS AND DISCUSSION

The findings of the current research were compared with the results collected, which was done by Wang *et al.* [23]. The cycle enthalpy variations with the water organic fluid were compared. The deviations between the results of the current research and benchmarks were computed using the following equation. The deviation was equal to 1% compared to the estimation by Wang *et al.* (Fig. 3).

$$\%Diff = \left(\frac{\left(\sum_{i=1}^{n} \frac{x_i - x_{i,benchmark}}{x_{i,benchmark}} \right)}{n} \right) \times 100. \quad (21)$$

In the modeling, ORC and water cycles are suggested as an upstream cycle to use the heat wasted from cement plant. Water, R134a and R245f as working fluids have been compared from energy and thermo-economic point of view. Also, considering the changes in such parameters as temperature, the main fluid pressure, the condenser pressure and the outlet pressure of the flash, the cycle's optimization is discussed. Comparing the thermal balance of the steam cycle and ORC cycles, it can be concluded that organic fluids. due to their unique condition and characteristics, could lead to a higher fluid flow which leads to a higher heat energy absorption of the gas in recovery boilers.

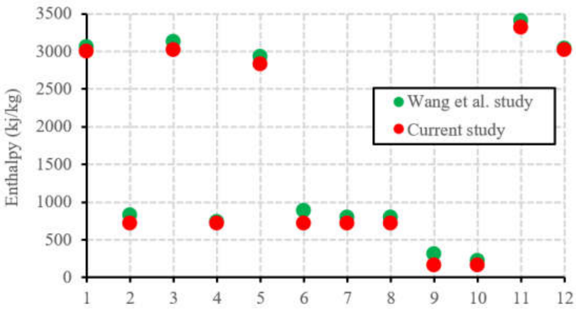

Fig. 3. The enthalpy changes of the cycle with the water-working fluid for present research and the Wang *et al.* study model

According to Table 4, it can be concluded that the cycle's thermal efficiency is greatly increased by organic fluid; while the temperature of the gas side and its flow rate in the two cycles is a certain amount and the same difference in thermal efficiency due to the cycle's parameters.

Organic fluid with higher exergy loss and higher power generation in the cycle and lower exergy loss has higher exergy efficiency. The difference in thermal efficiency is due to the cycle's parameters and the types of fluids. The power generated for the steam turbine is 4.8 MW; for organic fluid (R123), this is 5.06 MW, and for R245fa this is equal to 6.9 MW. The results approved the findings by Campana et al. [9]. By comparing the organic fluids, it can be realized that R245fa has higher exergy efficiency. Due to the existing limitations in the cycle, it can be seen that the only factor in increasing the efficiency is the change of fluids. In comparison with water, the SP1 boiler operating with organic cycles (R134a and R245fa) shows 72% and 71% increase in the amount of recycled energy. Also, R245fa shows a better heat recovery than other fluids which increase the heat transfer and power generation. Compared to the steam cycle, because of a high specific volume and an increasing flow rate in the organic cycle, the power of the pump is sharply increased. The use of the R245fa organic fluid increases the thermal efficiency up to 12%. The methodology followed in order to estimate the waste heat recovery potential in a large scale for cement industry is summarized in Figure 4. In this section, the results of an exergy analysis of the water cycle and the organic fluid are reviewed. As it can be seen for the organic fluid, the AQC boiler has the highest exergy loss. This increase in entropy is contributed to the temperature difference between the hot and cold stream. The total exergy loss for R134a is 4.9 MW while for water this would be 3.9 MW.

Tab. 4. Chemical exergy and molar mass of the main composition of the kiln feed

Case study	Water	R123	R245fa
W_{net} (MW)	4.848	5.06	6.81
Thermal efficiency (-)	6.54	8.56	12.02
Exergy efficiency (-)	33.88	24.34	26.06
Pump 1 (MW)	0.0036	0.1622	0.1326
Pump 2 (MW)	0.0285	0.0856	0.0389
AQC boiler exhaust temperature(°C)	99	99	99
SP_1 boiler exhaust temperature (°C)	214.31	215.75	215.92
SP_2 boiler exhaust temperature (°C)	214.31	215.75	215.92
Heat Recovery in AQC (MW)	7.20	12.42	12.36
Heat Recovery in SP_1 (MW)	7.20	5.34	8.84
Heat Recovery in SP_2 (MW)	5.77	14.62	19.84

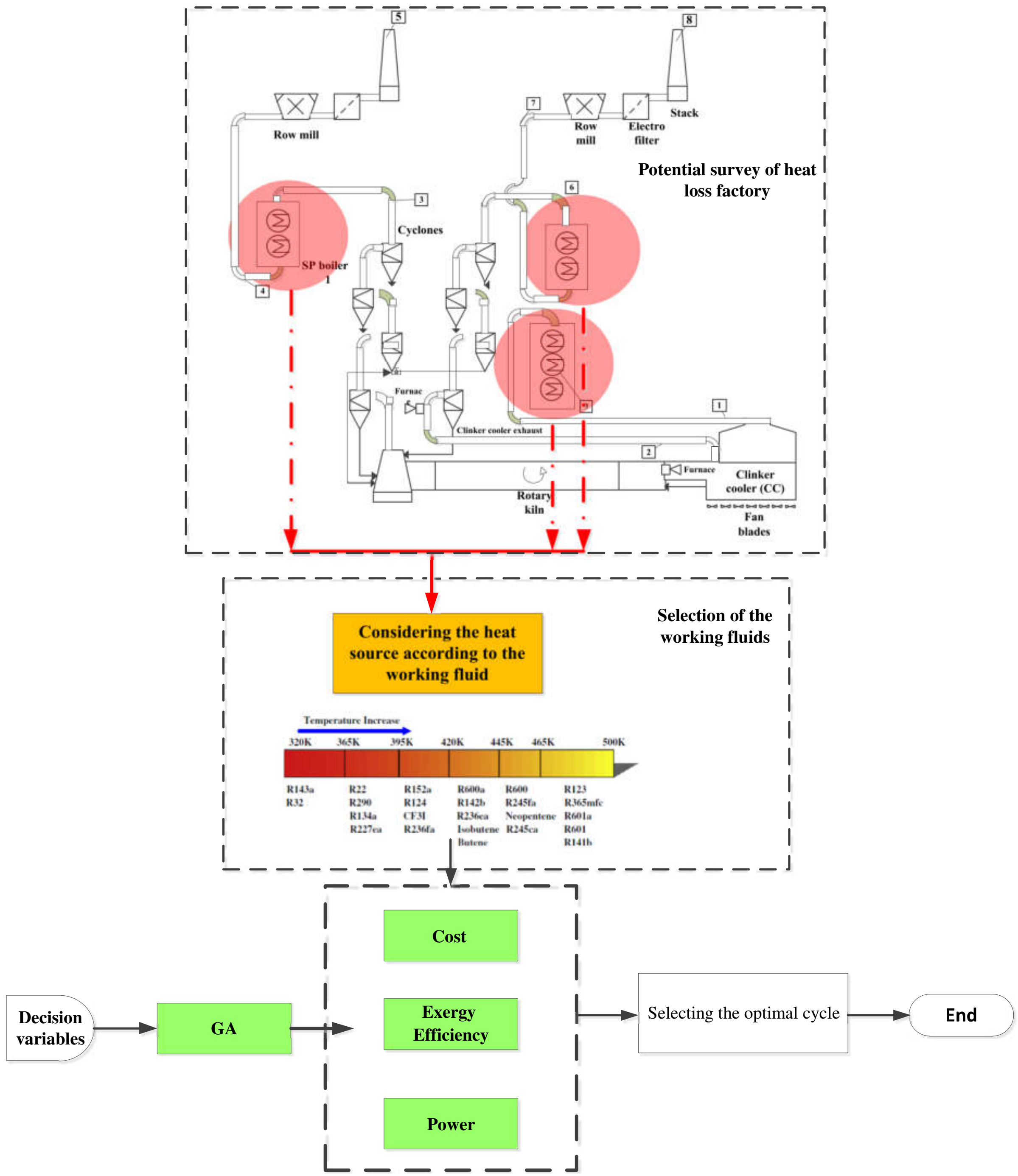

Fig. 4.Methodology of analysis scheme

The changes of exergy destruction and specific exergy for different working fluids between the cycle's components are shown in Figures 5a and 5b. Also, in this paper, according to the specific exergy function definition, heat transfer for each boiler is investigated. It can be concluded from the figure that the heat transfer process in boilers for water shows a better function in comparison with organic fluid. In the meantime, it can be seen that the R245fa fluid has a different exergy loss in comparing with the R134a fluid. The maximum exergy destruction is different between the cycle's components for these two fluids. As can be seen, the AQC boiler has the highest exergy degradation for organic fluids. This increase in entropy generation is due to the temperature difference between the hot and cold streams, which means a greater heat transfer between the two streams, and due to the high heat transfer between the other boilers.

The R134a organic fluid has a total degradation cycle of 4.9 MW, while the water fluid has 3.9 MW of exergy degradation. The organic fluid involves more exergy degradation, but by producing more power in the cycle and reducing exergy losses, it has a higher exergy efficiency. In the meantime, the R245fa fluid can be observed, which has a different exergy degradation than the R134a fluid. It can be related to the function of the R245fa fluid in various pressures and temperatures in comparison with R123. The results showed that the heat transfer recovered is higher for the organic fluid than for water. Figure 6 shows the ratio of the exergy loss of the components to total exergy for different working fluids between cycle components. As it can be seen, exergy loss in organic fluids allocates a greater region in comparison with water, which can be contributed to the low operating temperature of the organic fluids. The point to note in this graph is the ratio of turbine exergy loss to the total exergy loss. The steam quality of the turbine must be higher than 88% and this leads to higher exergy loss to the total exergy ratio in steam turbine in comparison with organic turbine. One of the advantages of using organic fluids is due to the related thermodynamic properties that can be used at lower pressures and without limitation.

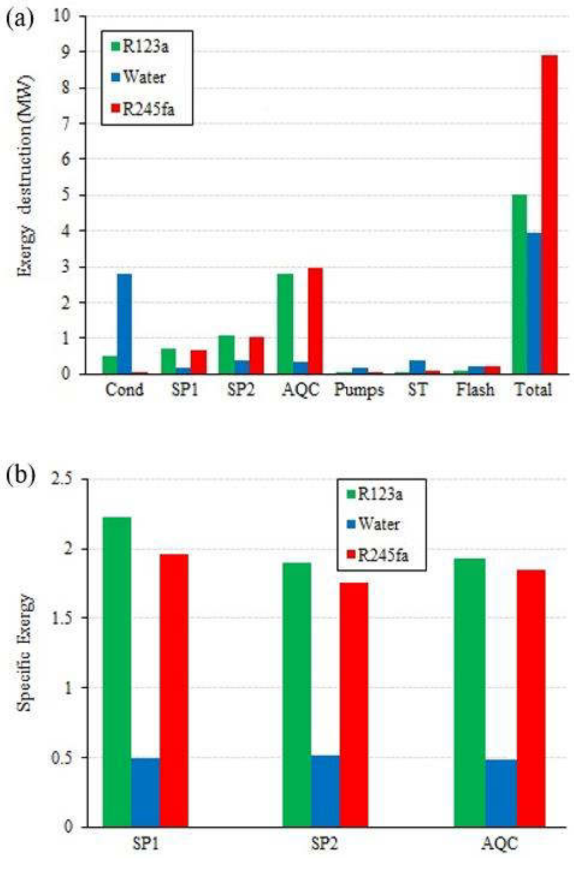

Fig. 5. Comparison of (a) exergy loss and (b) specific exergy for different working fluids between cycle components

The costs electricity produced have been calculated based on 6,073 hours of operation per year in the cement plant. In the case of the organic fluid, the steam turbine and the condenser, and for the water turbines and boilers, these have the highest costs in comparison with other components. In general, due to the higher power productivity of the organic fluids, the end cost of electricity is lower than for water and, also, R245fa has a lower cost in comparison with R123. The exergy efficiency of the cycle and the electricity cost are considered to be the objective functions. An optimizing curve for a working fluid is shown Figure 7.

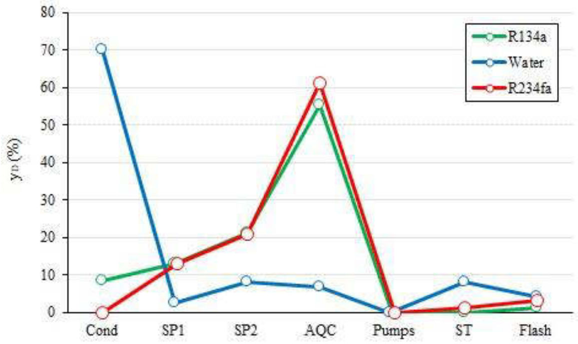

Fig. 6. The ratio of exergy loss of components to total exergy for different fluids

The followings are optimization limitation:

1. The outlet quality of organic fluid from the turbine shouldn't be less than 95%.
2. Output steam quality from flash is x=1.
3. Turbine outlet temperatures shouldn't be lower than of the outlet temperature of water from the condenser.
4. SP boilers outlet temperatures shouldn't be lower than 215°C.

As it can be seen, the R134a organic fluid has a more suitable pareto curve than other fluids. The R245fa fluid has many points, but because of the scale increase and the curve changes in a limited bound, it is shown with a dot. In Table 5, the cycle's parameters can be investigated based on the best spot of the pareto curve.

The higher cost of the organic fluid in the condenser can be contributed to the low surface tension when compared to water which, considering the condensation, the use of a fin and also the surface area extension (a higher surface means a higher cost) in these types of condensers are needed. On the other hand, from among the cycle's components, the pumps are the least expensive. Low electricity costs reflect the efficient use of waste heat in the cycle where, considering the use of heat exchangers and heat recovery boilers, this energy can be used with a minimum cost. Figure 8 is plotted based on the optimal point. According to Figure 8, R134a has greater efficiency than other working fluids. As can be seen, the Genetic Algorithm determines the optimum decision parameters (presented in Table 5) to improve the functions. Also, some parameter was selected to improve the advantages of the present cycle. In Figure 8, the condenser pressure is greater than ambient pressure. Therefore, it is necessary to use some systems such as an ejector. Due to lower energy and cooling water flow rate of the fluid heat exchanger for Ypsh, R134a is suggested for use.

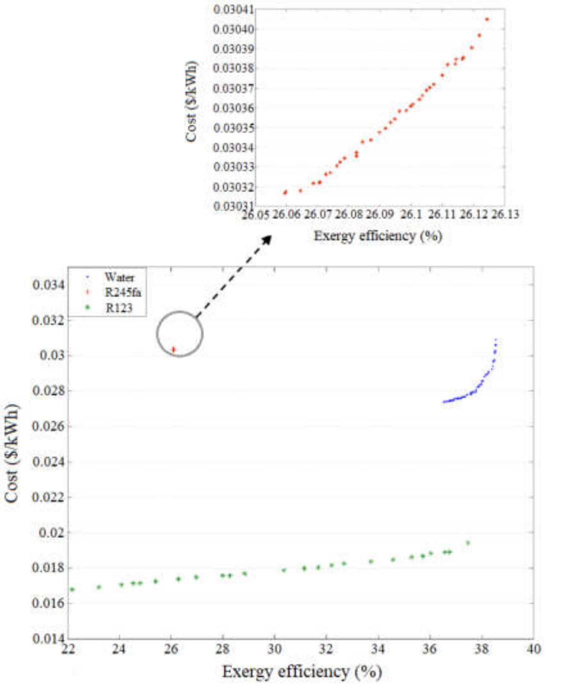

Fig. 7. Pareto curves for different fluids with the objective function

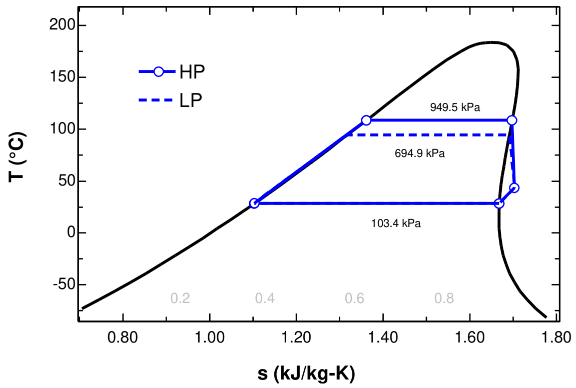

Fig. 8. T-S diagram for R134a in optimum point

Tab. 5. Chemical exergy and molar mass of the main composition of the kiln feed

Case studies (OPT)	Water	R123	R245fa
Wnet (MW)	5.04	9.73	6.81
Thermal efficiency (-)	6.77	17.17	12.02
Exergy efficiency (-)	38.14	26.16	26.11
pump1 (MW)	0.006	0.215	0.111
pump2 (MW)	0.0175	0.157	0.067
AQC boiler exhaust temperature (°C)	99	99	99
SP1 boiler exhaust temperature (°C)	215.0	215.0	215.0
SP2 boiler exhaust temperature (°C)	215.0	215.0	215.0
Heat Recovery in AQC (MW)	11.73	12.43	12.3631
Heat Recovery in SP1 (MW)	7.222	7.818	8.48
Heat Recovery in SP2 (MW)	5.80	21.25	19.859
x_{out} (-)	0.8803	1	1
Total exergy destruction (MW)	7.27	4.704	4.712
Cost ($/kWh)	0.0289	0.0185	0.0303

4. CONCLUSIONS

In this paper, an energy recovery system for the Neka cement plant was modeled using the MATLAB/Simulink package v9.10.0. The use of organic fluids can increase the thermal efficiency and power generation. In an energy analysis, it was found that due to the low yield of the organic fluid, the obtained flow rate in the boilers is greater than in water. In an organic cycle with R245fa and R134a as working fluids, the SP1 boiler shows a 72% and 71% increase in recycled energy and for AQC this increase is 153% and 244% respectively. Also, in a power generation system, R134a with 4% and R245fa with 28.8% increase, showed greater utilization of available energy in a cycle with the same structure. The increase in power is due to the greater use of energy available in the cement plant and the thermodynamic properties. The exergy analysis of the results showed that water has higher exergy efficiency in comparison with other organic fluids. Also, the turbine outlet steam quality limitation results in a higher exergy loss to the total exergy ratio for steam with a ratio of 10% than organic fluids (8%). By defining the specific exergy, it can be seen that the boilers which operate with water as working fluid show better performance in comparison with organic fluids. The results obtained from the genetic algorithm optimization have shown that in the desired cycle. the parameters can have a major role in changing the fluid performance and have a great impact on the exergy efficiency. Based on the best point, with an increase in power generation, R134a can be considered as a suitable fluid for the cycle, and it shows a 4.1% decrease in the total exergy loss of the system, and it also increases the production capacity from 5 to 9 MW.

Nomenclature

Symbols

Cp_g – Specific heat coefficient (kJ/kg-K)
e, ex – Exergy (kJ/kg)
Ex – Exergy flow (kW)
h_o – Inlet fluid flow enthalpy (kJ/ kg)
h_i – Outlet fluid flow enthalpy (kJ/ kg)
$\dot{m}_i$ – Inlet fluid flow rate (kg/s)
$\dot{m}_o$ – Outlet fluid flow rate (kg/s)
Q – Heat flow (kW)
T_o – Inlet fluid temperature (K)
T_i – Outlet fluid temperature (K)
wp – Pump Power (kW)
y_D – Exergy loss (-)
ρ – Density (kg/ m3)
ξ – Chemical exergy/energy ratio
ε – Total cycle exergy efficiency (-)
η_{ex} – Exergy efficiency (-)
η_p – Pump efficiency (-)

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Biographical notes

Biographical notes were not provided.